Appendix B
Filter Design

B-1. General

The objective of filters and drains used as seepage control measures for embankments is to efficiently control the movement of water within and about the embankment. In order to meet this objective, filters and drains must, for the project life and with minimum maintenance, retain the protected materials, allow relatively free movement of water, and have sufficient discharge capacity. For design, these three necessities are termed piping or stability requirement, permeability requirement, and discharge capacity, respectively. This appendix explains how these requirements are met for cohesionless and cohesive materials, and provides general construction guidance for installation of filters and drains. The terms filters and drains are sometimes used interchangeably. Some definitions classify filters and drains by function. In this case, filters must retain the protected soil and have a permeability greater than the protected soil but do not need to have a particular flow or drainage capacity since flow will be perpendicular to the interface between the protected soil and filter. Drains, however, while meeting the requirements of filters, must have an adequate discharge capacity since drains collect seepage and conduct it to a discharge point or area. In practice, the critical element is not definition, but recognition, by the designer, when a drain must collect and conduct water. In this case the drain must be properly designed for the expected flows. Where it is not possible to meet the criteria of this appendix, the design must be cautiously done and based on carefully controlled laboratory filter tests (Perry 1987).

B-2. Stability

Filters and drains[1] allow seepage to move out of a protected soil more quickly than the seepage moves within the protected soil. Thus, the filter material must be more open and have a larger grain size than the protected soil. Seepage from the finer soil to the filter can cause movement of the finer soil particles from the protected soil into and through the filter. This movement will endanger the embankment.[2] Destruction of the protected soil structure may occur due to the loss of material. Also, clogging of the filter may occur causing loss of the filter's ability to remove water from the protected soil. Criteria developed by many years of experience are used to design filters and drains which will prevent the movement of protected soil into the filter. This criterion, called piping or stability criterion, is based on the grain-size relationship between the protected soil and the filter. In the following paragraphs, the lower case "d" is used to represent the grain size for the protected (or base) material and the upper case "D" the grain size for the filter material. Determine filter gradation limits using the following steps (Soil Conservation Service 1986):

a. Determine the gradation curve (grain-size distribution) of the base soil material. Use enough samples to define the range of grain size for the base soil or soils and design the filter gradation based on the base soil that requires the smallest D_{15} size.

b. Proceed to step *d* if the base soil contains no gravel (material larger than No. 4 (4.75 mm) sieve).

c. Prepare adjusted gradation curves for base soils with particles larger than the No. 4 (4.75 mm) sieve:

(1) Obtain a correction factor by dividing 100 by the percent passing the No. 4 (4.75 mm) sieve.

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[1] In paragraphs B-2 and B-3 the criteria apply to drains and filters; for brevity, only the word filter will be used.
[2] In practice, it is normal for a small amount of protected soil to move into the filter upon initiation of seepage. This action should quickly stop and may not be observed when seepage first occurs. This is one reason that initial operation of embankment seepage control measures should be closely observed by qualified personnel.

(2) Multiply the percentage passing each sieve size of the base soil smaller than No. 4 (4.75 mm) by the correction factor from step *c*(1).

(3) Plot these adjusted percentages to obtain a new gradation curve.

(4) Use the adjusted curve to determine the percent passing the No. 200 (0.075 mm) sieve in step *d*.

d. Place the base soil in a category based on the percent passing the No. 200 (0.075 mm) sieve in accordance with Table B-1.

Table B-1
Categories of Base Soil Materials

Category	Percent finer than the No. 200 (0.075 mm) sieve
1	85
2	40-85
3	15-39
4	15

e. Determine the maximum D_{15} size for the filter in accordance with Table B-2. Note that the maximum D_{15} is not required to be smaller than 0.20 mm.

Table B-2
Criteria for Filters

Base soil category	Base soil description, and percent finer than No. 200 (0.075 mm) sieve[1]	Filter criteria in terms of maximum D_{15} size[2]	Note
1	Fine silts and clays; more than 85% finer	$D_{15} \leq 9 \times d_{85}$	(1)
2	Sands, silts, clays, and silty and clayey sands; 40 to 85% finer.	$D_{15} \leq 0.7$ mm	
3	Silty and clayey sands and gravels; 15 to 39% finer	$D_{15} \leq \frac{40-A}{40-15} \{(4 \times d_{85}) - 0.7\text{ mm}\} + 0.7\text{ mm}$	(2),(3)
4	Sands and gravels; less than 15% finer.	$D_{15} \leq 4$ to $5 \times d_{85}$	(4)

[1] Category designation for soil containing particles larger than 4.75 mm is determined from a gradation curve of the base soil which has been adjusted to 100% passing the No. 4 (4.75 mm) sieve.
[2] Filters are to have a maximum particle size of 3 in. (75 mm) and a maximum of 5% passing the No. 200 (0.075 mm) sieve with the plasticity index (PI) of the fines equal to zero. PI is determined on the material passing the No. 40 (0.425 mm) sieve in accordance with EM 1110-2-1906. To ensure sufficient permeability, filters are to have a D_{15} size equal to or greater than $4 \times d_{15}$ but no smaller than 0.1 mm.

NOTES:
(1) When $9 \times d_{85}$ is less than 0.2 mm, use 0.2 mm.
(2) A = percent passing the No. 200 (0.075 mm) sieve after any regrading.
(3) When $4 \times d_{85}$ is less than 0.7 mm, use 0.7 mm.
(4) In category 4, the d_{85} can be based on the total base soil before regrading. In category 4, the $D_{15} \leq 4 \times d_{85}$ criterion should be used in the case of filters beneath riprap subject to wave action and drains which may be subject to violent surging and/or vibration.

f. To ensure sufficient permeability, set the minimum D_{15} greater than or equal to 3 to 5 $\times$ maximum d_{15} of the base soil before regrading, but no less than 0.1 mm.

g. Set the maximum particle size at 3 in. (75 mm) and the maximum passing the No. 200 (0.075 mm) sieve at 5 percent. The portion of the filter material passing the No. 40 (0.425 mm) sieve must have plasticity index (PI) of zero when tested in accordance with EM 1110-2-1906.

h. Design the filter limits within the maximum and minimum values determined in steps *e*, *f*, and *g*. Standard gradations may be used if desired. Plot the limit values and connect all the minimum and maximum points with straight lines. To minimize segregation and related effects, filters should have relatively uniform grain-size distribution curves, without "gap grading"--sharp breaks in curvature indicating absence of certain particle sizes. This may require setting limits that reduce the broadness of filters within the maximum and minimum values determined. Sand filters with D_{90} less than about 20 mm generally do not need limitations on filter broadness to prevent segregation. For coarser filters and gravel zones that serve both as filters and drains, the ratio D_{90}/D_{10} should decrease rapidly with increasing D_{10} size. The limits in Table B-3 are suggested for preventing segregation during construction of these coarser filters.

Table B-3
D_{10} and D_{90} Limits for Preventing Segregation

If minimum D_{10}, mm	Then maximum D_{90}, mm
<0.5	20
0.5 - 1.0	25
1.0 - 2.0	30
2.0 - 5.0	40
5.0 - 10	50
10 - 50	60

B-3. Permeability

The requirement that seepage move more quickly through the filter than through the protected soil (called the permeability criterion) is again met by a grain-size relationship criterion based on experience:

Permeability

$$\frac{\text{15 percent size of filter material}}{\text{15 percent size of protected soil}} \geq 3 \text{ to } 5 \qquad \text{(B-1)}$$

Permeability of a granular soil is roughly proportional to the square of the 10 to 15 percent size material. Thus, the permeability criterion ensures that filter materials have approximately 9 to 25 or more times the permeability of the protected soil. Generally, a permeability ratio of at least 5 is preferred; however, in the case of a wide band of uniform base material gradations, a permeability ratio as low as 3 may be used with respect to the maximum 15 percent size of the base material. There may be situations, particularly where the filter is not part of a drain, where the permeability of the filter is not important. In those situations, this criterion may be ignored.

B-4. Applicability

The filter criteria in Table B-2 and Equation B-1 are applicable for all soils (cohesionless or cohesive soils) including dispersive soils (Sherard and Dunnigan 1985). However, laboratory filter tests are recommended for dispersive soils, very fine silt, and very fine cohesive soils with high plastic limits.

B-5. Perforated Pipe[1]

The following criteria are applicable for preventing infiltration of filter material into perforated pipe, screens, etc.):

$$\frac{\text{minimum 50 percent size of filter material}}{\text{hole diameter or slot width}} \geq 1.0 \qquad \text{(B-2)}$$

In many instances a filter material meeting the criteria given by Table B-2 and Equation B-1 relative to the material being drained is too fine to meet the criteria given by Equation B-2. In these instances, multilayered or "graded" filters are required. In a graded filter each layer meets the requirements given by Table B-2 and Equation B-1 with respect to the pervious layer with the final layer in which a collector pipe is bedded also meeting the requirements given by Equation B-2. Graded filter systems may also be needed when transitioning from fine to coarse materials in a zoned embankment or where coarse material is required for improving the water carrying capacity of the system.

B-6. Gap-Graded Base

The preceding criteria cannot, in most instances, be applied directly to protect severely gap- or skip-graded soils. In a gap-graded soil such as that shown in Figure B-1 the coarse material simply floats in the matrix of fines. Consequently, the scattered coarse particles will not deter the migration of fines as they do in a well-graded material. For such gap-graded soils, the filter should be designed to protect the fine matrix rather than the total range of particle sizes. This is illustrated in Figure B-1. The 85 percent size of the total sample is 5.2 mm. Considering only the matrix material, the 85 percent size would be 0.1 mm resulting in a much finer filter material being required. This procedure may also be followed in some instances where the material being drained has a very wide range of particle sizes (e.g., materials graded from coarse gravels to significant percentages of silt or clay). For major structures such a design should be checked with filter tests.

B-7. Gap-Graded Filter

A gap-graded filter material must never be specified or allowed since it will consist of either the coarse particles floating in the finer material or the fine material having no stability within the voids produced by the coarse material. In the former case the material may not be permeable enough to provide adequate drainage. The latter case is particularly dangerous since piping of the protected material can easily occur through the relatively large, loosely filled voids provided by the coarse material.

B-8. Broadly Graded Base

One of the more common soils used for embankment dams is a broadly graded material with particle sizes ranging from clay sizes to coarse gravels and including all intermediate sizes. These soils may be of glacial, alluvial-colluvial, or weathered rock origin. As noted by Sherard, since the 85 percent size of the soil is commonly on the order of 20 to 30 mm, a direct application of the stability criteria $D_{15}/d_{85} \leq 4$ to 5 would allow very coarse uniform gravel without sand sizes as a downstream filter, which would not be satisfactory (Sherard 1979). The typical broadly graded soils fall in Soil Category 2 in Table B-2 and require a sand or gravelly filter with $D_{15} \leq 0.7$ mm.

[1] EM 1110-2-2300 states, "Collector pipe should not be placed within the embankment, except at the downstream toe, because of the danger of either breakage or separation of joints, resulting from fill placement and compaction operations, or settlement, which might result in either clogging and/or piping."

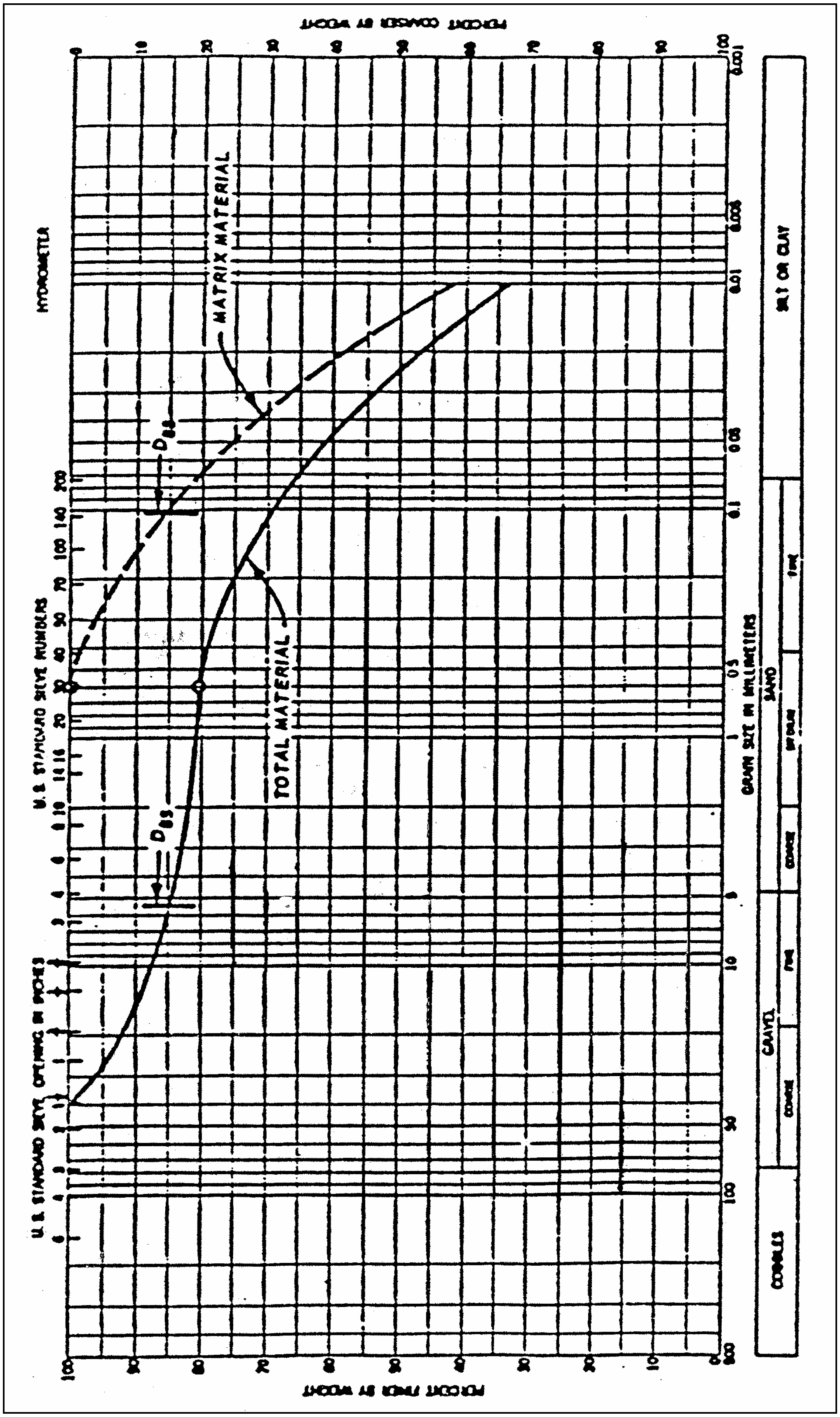

Figure B-1. Analysis of gap-graded material (from EM 1110-2-1913)

B-9. Example of Graded Filter Design for Drain

Seldom, if ever, is a single gradation curve representative of a given material. A material is generally represented by a gradation band which encompasses all the individual gradation curves. Likewise, the required gradation for the filter material is also given as a band. The design of a graded filter which shows the application of the filter criteria where the gradations are represented by bands is illustrated in Figure B-2. A typical two-layer filter for protecting an impervious core of a dam is illustrated. The impervious core is a fat clay (CH) with a trace of sand which falls in Category 1 soil in Table B-2. The criterion $D_{15} \leq 9 \times d_{85}$ is applied and point "a" is established in Figure B-2. Filter material graded within a band such as that shown for filter material A in Figure B-2 is acceptable based on the stability criteria. The fine limit of the band was arbitrarily drawn and in this example is intended to represent the gradation of a readily available material. A check is then made to ensure that the 15 percent size of the fine limit of the filter material band (point b) is equal to or greater than 3 to 5 times the 15 percent size of the coarse limit of the drained material band (point c). Filter A has a minimum D_{10} size and a maximum D_{90} size such that, based on Table B-3, segregation during placement can be prevented. Filter material A meets both the stability and permeability requirements and is a suitable filter material for protecting the impervious core material. The second filter, filter material B, usually is needed to transition from a fine filter (filter material A) to coarse materials in a zoned embankment dam. Filter material B must meet the criteria given by Table B-2 with respect to filter material A. For stability, the 15 percent size of the coarse limit of the gradation band for the second filter (point d) cannot be greater than 4 to 5 times the 85 percent size of the fine limit of the gradation band for filter material A (point e). For permeability, the 15 percent size of the fine limit (point f) must be at least 3 to 5 times greater than the 15 percent size of the coarse limit for filter material A (point a). With points d and f established, the fine and coarse limits for filter material B may be established by drawing curves through the points approximately parallel to the respective limits for filter material A. A check is then made to see that the ratio of maximum D_{90}/minimum D_{10} size of filter material B is approximately in the range as indicated in Table B-3. A well-graded filter which usually would not meet the requirements in Table B-3 may be used if segregation can be controlled during placement. Figure B-2 is intended to show only the principles of filter design. The design of thickness of a filter for sufficient seepage discharge capacity is done by applying Darcy's Law, $Q = kia$ (an example is presented in Chapter 8 of EM 1110-2-1901).

B-10. Construction

EM 1110-2-1911 provides guidance for construction. Major concerns during construction include:

a. Prevention of contamination of drains and filters by runoff containing sediment, dust, construction traffic, and mixing with nearby fine-grained materials during placement and compaction. Drain and filter material may be kept at an elevation higher than the surrounding fine-grained materials during construction to prevent contamination by sediment-carrying runoff.

b. Prevention of segregation, particularly well-graded filters, during handling and placement.

c. Proper in-place density is usually required to be an average of 85 percent relative density with no area less than 80 percent relative density. Granular materials containing little or no fines should be saturated during compaction to prevent "bulking" (low density) which can result in settlement when overburden materials are placed and the drain is subsequently saturated by seepage flows.

d. Gradation should be monitored closely so that designed filter criteria are met.

e. Thickness of layers should be monitored to ensure designed discharge capacity and continuity of the filter.

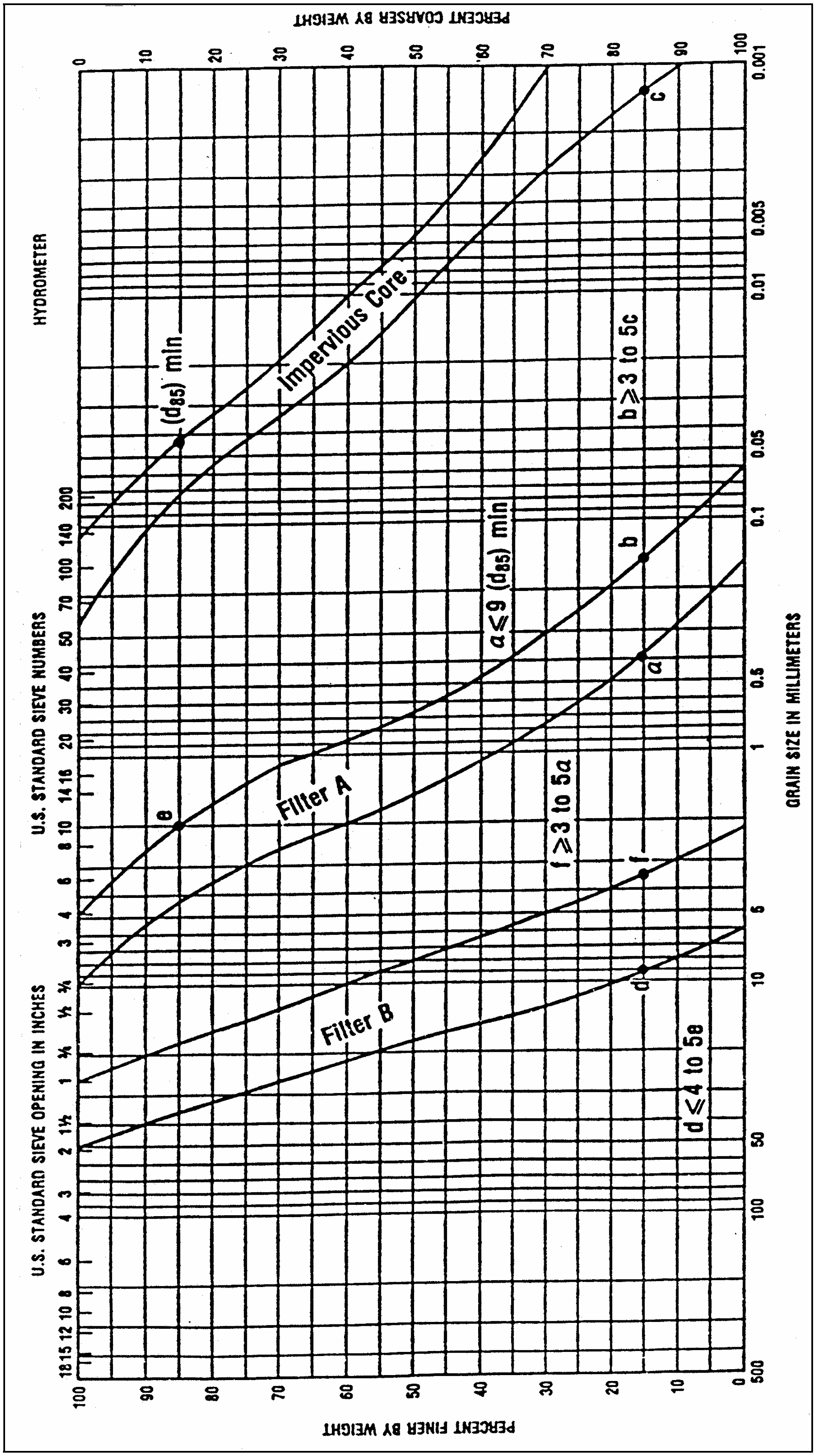

Figure B-2. Illustration of the design of a graded filter

Thus, quality control/assurance is very important during filter construction because of the critical function of this relatively small part of the embankment.

B-11. Monitoring

Monitoring of seepage quantity and quality (see Chapter 13 of EM 1110-2-1901 for methods of monitoring seepage) once the filter is functioning is very important to the safety of the embankment. An increase in seepage flow may be due to a higher reservoir level or may be caused by cracking or piping. The source of the additional seepage should be determined and action taken as required (see Chapters 12, 13, and 14 of EM 1110-2-1901). Decreases in seepage flows may also signal dangers such as clogging of the drain(s) with piped material, iron oxide, calcareous material, effects of remedial grouting, etc. Again, the cause should be determined and appropriate remedial measures taken. Drain outlets should be kept free of sediment and vegetation. In cold climates, design or maintenance measures should be taken to prevent clogging of drain outlets by ice.